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RECENT CHANGES OF LEVEL IN THE YAKUTAT BAY REGION, ALASKA*

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Introductory Considerations

EARTHQUAKE OF SEPTEMBER, 1899

The San Francisco *Examiner* for September 25, 1899, contains a letter sent from Yakutat, Alaska, September 17, by the Reverend Sheldon Jackson, giving a vivid but exaggerated account of a series of earthquake shocks beginning September 3 and still continuing at the date of writing the letter. Some of the statements are evidently erroneous, but many

of them were verified by us.* The first shock occurred September 3, and there were shocks at intervals until September 10, when, at 9.20 a m, they began to be alarming. There were 52 shocks, culminating in one of great violence at 3 p m. The land swayed, the waters of the bay rose and fell 8 to 10 feet every few minutes, and violent eddies were set up in the harbor, washing into the sea an Indian burial ground at Port Mulgrave, opposite Yakutat. Most of the natives and whites were panic-stricken, abandoning their houses and retreating to tents on the neighboring morainic hills. There was another violent earthquake September 15, and other shocks until September 20.

A party of prospectors was encamped on the shore of Russell fiord near the Hubbard glacier, and their experiences, as related to us by one of the party, Mr Flenner, were full of excitement and danger. The ground rocked so that they could not remain on their feet; the front of Hubbard glacier was broken into fragments; great water waves washed them and their equipment back on the moraine; a lake, marginal to Hubbard glacier, burst its barrier; and huge avalanches descended the mountain sides. The prospectors finally escaped with such equipment as they could save, though on their way to Yakutat they were again placed in danger by the earthquake of September 15. That the experiences related by Mr Flenner are in the main correct there can be no doubt, and that his party escaped destruction is remarkable, in view of the clear evidence of the cataclysm still recorded along the shores of the bay. So far as could be learned, there was no loss of human life; but at that time of year the natives are not liable to be in the bay, and their village is from 15 to 30 miles or more from the centers of disturbance.

It is a well known fact that an earthquake shock in September, 1899, did such damage to the Muir glacier on Glacier bay, 140 miles southeast of Yakutat, as to render access to it impossible by the tourist steamers for several seasons. It will be most interesting to learn whether the phenomena so clearly recorded around the shores of Yakutat bay are duplicated in the Glacier Bay region.

Although we knew in general terms that there had been an earthquake in the Yakutat Bay region in 1899, we were totally unprepared for the clear and striking proof of it that we found, or for the evidence of the remarkable changes of level which accompanied it. It is the purpose of this paper to state with some fullness the evidence of the changes which were associated with this earthquake and to venture some interpretations based on this evidence. Altogether it is the most remarkable instance of

* The only reason for referring to this is that it is the only first-hand published account of the earthquake which we have seen.

change of level so far recorded; and the fact that it is possible to assign to it an exact date is of considerable importance.

LOCATION AND GENERAL PHYSIOGRAPHY

Yakutat bay is a deep indentation in the unbroken concave stretch of coastline between Cross sound and Controller bay. This smooth coast is backed by the lofty Fairweather and Saint Elias ranges, which reach their culminating heights in mounts Saint Elias and Logan, 18,000 and 19,540 feet respectively. The mountains do not, however, rise directly from the sea, but are faced by a low foreland, or coastal plain, of glacial debris, broadening toward the northwest, and on the northwest side of Yakutat bay still occupied by the ice plateau of Malaspina glacier. Yakutat bay, which lies about 40 miles southeast of mount Saint Elias, pierces the Yakutat foreland as a V-shaped bay. On its western side the bay is bordered by the low foreland (here glacial gravels from the Malaspina and other existing glaciers); but on the eastern and southeastern sides the foreland forms the coast for only about half its length (see plate 23, opposite page 54). This part of the southeastern shoreline (see plate 16, figure 2) is very irregular and is fronted by an archipelago of low islands of glacial debris. The northern half of the bay has for its eastern shore a mountainous land rising abruptly to elevations of 3,000 to 4,550 feet. This shore is straight and precipitous, and the mountain front, against which the foreland is built, also rises abruptly along a straight line which truncates the mountain spurs* (see plate 22, figure 1).

Yakutat bay merges northward into a narrower arm, called Disenchantment bay, which is a true fiord, walled on both sides by steeply rising mountains. It extends from points Funston and Latouche on the south to Hubbard glacier, which forms its head with an ice cliff about 4 miles in length. A second tidal glacier, the Turner, enters the fiord through a valley in its west wall.

At Hubbard glacier the inlet turns at a high angle, and thence on to its head is called Russell fiord. North, northeast, and northwest of this, mountains rise to elevations of 10,000 to 16,000 feet, but along the immediate shores of the fiord the mountains rise abruptly to elevations of only 2,000 to 6,000 feet. Russell fiord, which extends back toward the Pacific, roughly parallel to Disenchantment and Yakutat bays, is divisible into three sections: (1) a northwest arm, with straight mountainous shores; (2) a longer south arm, with a much more irregular mountainous shoreline; and (3) the head of the bay, an expanded extension of the

* Russell (see Nat. Geog. Mag., vol. iii, 1891, pp. 57 and 83) infers faulting here on the basis of topographic form and geological structure.

inlet where it passes beyond the mountain front out into the foreland. A small bay, Seal bay, up whose valley lies Hidden glacier, forms the greatest irregularity in the coastline of the south arm; but at the angle between the south and northwest arms a large fiord extends eastward, under the name of Nunatak fiord. The tidal Nunatak glacier forms its head.

The entire inlet,—Yakutat bay, Disenchantment bay, and Russell Fiord—omitting its branch, the Nunatak fiord, has the general shape of a bent arm with the shoulder at the Pacific, the elbow at the head of Disenchantment bay, and the fist at the expanded head of the bay where the fiord extends into the foreland to within 13 or 14 miles of the ocean. From the ocean around to the head of Russell fiord by boat is a distance of 70 or 75 miles. Thus our studies extended along more than 150 miles of shoreline in the bay and fiord, all parts of which were seen and most of which were studied critically.

Everywhere the indications are that the fiord is deep. Soundings have been made by the U. S. Coast Survey in Yakutat bay, showing an irregular bottom deepening toward Disenchantment bay. At the mouth of the latter bay, near point Latouche, there is a depth of 167 fathoms; and between Haenke island and Hubbard glacier Russell reports 40 to 60 fathoms. Beyond this no accurate soundings have been made; but the shape of the coast and the absence of kelp indicate deep water throughout the fiord.

GEOLOGICAL STRUCTURE

The northeastern shore of Russell fiord, from Hubbard glacier to Nunatak fiord, is made of highly inclined slates of undetermined age. Our expeditions into the mountains along this shore discovered a variety of crystalline rocks, both igneous and metamorphic, and the glaciers bring down only these classes of rock. All the north shore and the eastern two-thirds of the south shore of Nunatak fiord are also bordered by crystalline rocks—granite, and steeply dipping gneiss, schist, slate and stretched conglomerate. These crystalline rocks end abruptly against a younger, practically unmetamorphosed series both in the Hidden Glacier valley and on the south shore of Nunatak fiord. This line of separation, interpreted as a fault, if continued would extend down the northwest arm of Russell fiord, on one of whose shores the rocks are crystalline, while on the other (southwest) the unmetamorphosed series is present.

From these crystalline rocks to the foreland there is a complex, called the Yakutat series by Russell, forming all the mountains bordering this part of the fiord. It consists of thinly bedded black shales and sandstones,

thick beds of black shale conglomerate, and a massive gray rock which, with the incomplete petrographic work so far done on it, is tentatively classed as an indurated tuff. There are other rocks in lesser quantities, and the entire mass is complexly folded and faulted, both on a large and small scale. Small faults and folds occur in all the outcrops, and frequently a score or more appear in a single outcrop a few square yards in area. The series is literally crushed and "kneaded." The Yakutat rocks are very barren of fossils, and from those which we were able to collect it has not been possible to determine their age. Ulrich* classifies this series as Liassic.

A third series of rocks occurs in a few outcrops two or three miles from the head of Yakutat bay, on the west side. These rocks are mainly gray sandstones, clays, and carbonaceous shales, with some small beds of lignite coal. They stand at a high angle, but are not complexly folded and faulted like the Yakutat series, from which they are apparently separated by a fault. A tentative determination of Pliocene age, based on a preliminary examination of the plant fossils, has been placed by Knowlton on this coal-bearing series.

Outside of the mountain front, as already stated, a foreland of glacial gravels extends to the sea; but near the head of Russell fiord it is underlaid by planated Yakutat series and granitic rocks. Elsewhere no hard rock was found in the foreland; but a low, butte-like hill rising above it some distance from the mountains is evidently rock.

PREVIOUS EXPLORATIONS

Professor I. C. Russell explored Yakutat bay and Disenchantment bay in 1890.† He describes the earlier explorations, discusses the general physiography and geology, and pays particular attention to the glaciers. In 1891‡ Russell extended his explorations to the head of Russell fiord. In his descriptions he clearly points out the faulted and folded condition of the rocks of the Yakutat series and assigns to faulting an important part in the production of the physiography of the region. With the exception of some gravel terraces, which our work leads us to assign to other origin, Russell mentions no elevated shorelines. He does call attention to a submerged forest at the head of the bay which we also saw.

The Harriman expedition visited the inlet in June, 1899, three months before the earthquake, and went to the head of Russell fiord, landing at several points, among others on Haenke island, which now has very dis-

* Harriman Alaska Expedition, vol. iv, 1904, pp. 125-146.
† Nat. Geog. Mag., vol. iii, 1891, pp. 53-203.
‡ Thirteenth Annual Report U. S. Geol. Survey, 1891-2, part ii, pp. 1-91.

tinct shorelines elevated 17 to 19 feet. Among those who landed here was Dr G. K. Gilbert, whose critical studies and interpretations of abandoned shorelines are well known. The fact that he does not mention an uplift there, where the uplifted shorelines are very perfect, is suggestive evidence that they had not then been upraised; and this conclusion is amply verified by other evidence. Doctor Gilbert describes the general physiography of the region, giving especial attention to the glaciers, in his book which forms a part of the series of Harriman Expedition monographs.*

In July, 1901, a U. S. Fish Commission expedition, under the direction of Ensign Cyrus R. Miller, went up the fiord; and while his description gives no information of the change in level which had occurred, one of his photographs* plainly shows a part of the elevated shoreline of Haenke island. He does state, however (page 384) that around the circular lake on the foreland at the mountain base (to which we have given the name Miller lake), the eastern and western shores were covered with dead spruce and hemlock, said to have been killed during the earthquake of September, 1899. This lake lies on one of our inferred fault lines.

GENERAL STATEMENT OF OBSERVATIONS IN 1905

Our work along the shores of Yakutat bay and Russell fiord extended from June 24 to September 2. We found that the shorelines of the inlet had been differentially deformed and the mountain rocks in places shattered by minor faulting. Parts of the coast show no change in level; some areas are depressed; but throughout most of the coast there has been uplift of from one to ten feet. Locally the uplift far exceeds this figure, along one shore attaining a maximum of 47 feet 4 inches. The evidence of these changes is varied and can best be presented under different headings.

Physiographic Evidences of recent Uplift

ELEVATED ROCK BENCHES

At various points about the shores of the fiord, rock benches stand higher than the cutting zone of present waves. They vary in width from a foot or two to 30 or 40 feet, and are planed across all sorts of structures and all kinds of rocks. In numerous instances small streams cascade over their edge, owing to the introduction of the hanging valley condition by the uplift. In general the benches are broadest where the rocks are

* Alaska—vol. iii, Glaciers and Glaciation, by G. K. Gilbert, 1904, pp. 45-70.
† Plate xliv, opposite p. 392, Bull. U. S. Fish Comm., vol. xxi, 1901.

weakest or exposure to wave cutting was greatest. On the promontories they usually form flat-topped benches, and along straight reaches of rocky coast angular notches planed in the rocks, frequently with unconsumed reefs and stacks on the outer margin. These benches (see plate 13, figure 1) often form an opportunity for travel along the coast in places where at the present stand of the sea it is impossible to even land from a boat. In fact, along the present coast many of the headlands rising out of deep water have been so slightly affected by the waves during the brief period since the uplift that even the glacial scratches and polishing have not been removed by the waves, and can be actually traced continuously from above high tide down to and beneath the low-tide mark.

Where the uplift has been slight—that is, not over a foot or two—it is often difficult to distinguish the older benches from those now forming, since they merge into one another; but in most of the fiord the benches are so clear cut, and so elevated, that from these alone one could be certain of the presence of an upraised strand.

Naturally we considered the possibility of other explanations, such as glacial marginal channels and the action of iceberg waves at a time when tidal glaciers extended farther down the fiord; but it required only a little observation to disprove these hypotheses in most places. The widespread and uniform character of the phenomenon, and the almost universal association of barnacles and other marine organisms, still clinging to the rock on the benches, sufficed to effectively dispose of other explanations than uplift.

In two or three places, notably near the Hubbard and Nunatak glaciers, there is evidence of wave cutting at a higher level than at present, apparently performed when the ice-fronts were nearer these shores and the waves generated by calving of icebergs more effective. Such shorelines are not more than two or three feet higher than normal, and are not to be confused with the well defined elevated shorelines, which in reality attain their best development not near, but at a distance from, the tidal glaciers.

ELEVATED SEA CAVES AND CHASMS

Some of the rocks of the Yakutat series, especially the thin bedded black shales and sandstones, yield more readily to wave attack than others, such as the indurated tuff and massive conglomerate. Accordingly the shores of the inlet furnish many instances of sea caves and chasms; but in those parts of the coast where the wave-cut benches are elevated these phenomena are found in association with the uplifted shoreline and not with the present stand of the sea (see plate 13, figure 2). The caves

FIGURE 1.—LOOKING NORTH ALONG EAST SHORE OF DISENCHANTMENT BAY, JUST NORTH OF HAENKE ISLAND

Shows 17-foot elevated rock bench on which barnacles still cling

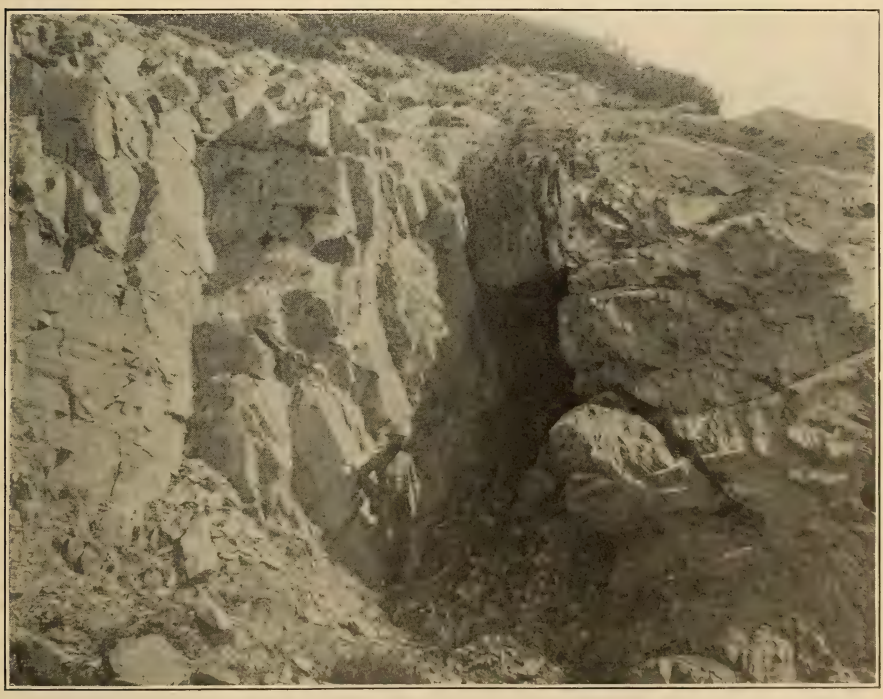


FIGURE 2.—ELEVATED SEA CAVE ON EAST SIDE OF DISENCHANTMENT BAY, JUST NORTH OF HAENKE ISLAND

Uplift is 17 to 18 feet. Base of cave now well above high tide. In middle foreground, below level of cave, is annual land plant

FIGURE 1.—ELEVATED BEACH ON ROCK BENCH LEVEL ON EAST SIDE OF RUSSELL FIORD

Locality is 4 to 5 miles south of Russell cove. Elevation here is 6 feet 2 inches. New vegetation in foreground. Old cottonwoods and alders above beach level

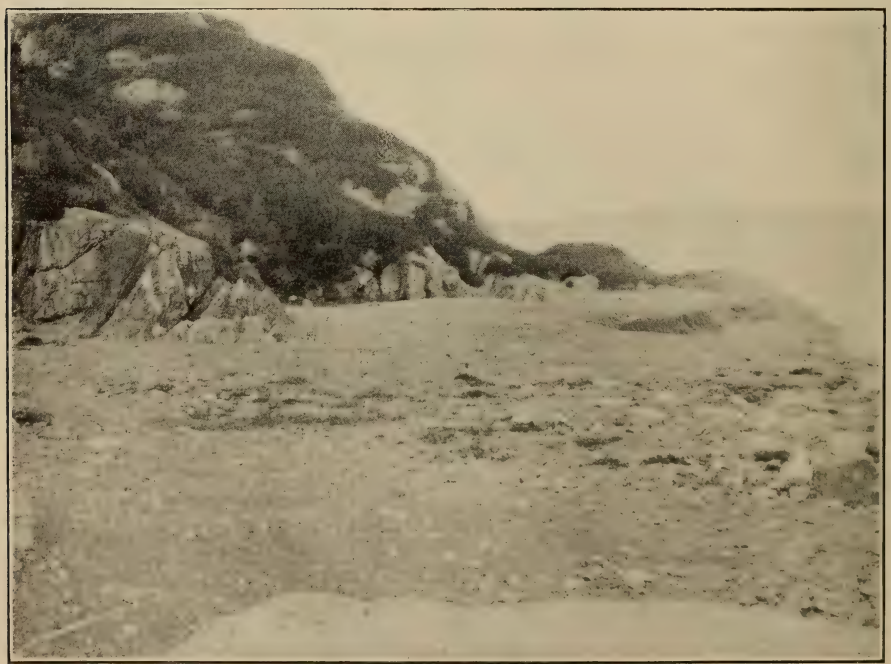


FIGURE 2.—ELEVATED BEACH (37 FEET) ON WEST SIDE OF DISENCHANTMENT BAY, ABOVE POINT FUNSTON

and chasms still contain shingle, but annual plants and even shrubs grow in it, often rising up against and shadowing dead barnacles that still cling to the walls of the chasm—a new life springing up in the habitat of the old. Some caves have been made entirely dry, some only half dry, the tide still rising into their lower portions. One enormous cave, on the south side of Haenke island, rises twice as high above high tide as it did before the uplift, which was here about 18 feet. Waves still enter its mouth, but now never rise high enough to reach the back of the cave. Scores of similar cases were observed in association with the elevated rock benches, and in various places.

ELEVATED BEACHES

Tying bench to bench and foreland to foreland, at appropriate levels, are the perfectly preserved sand, gravel, and boulder beaches of the lower stand of the land (see plates 14 and 15). Excepting near stream mouths, they are all in the form of pocket beaches, for on this straight coast, with rocky shores, limited supply of rock fragments, and deep water offshore, bars and spits have not usually been developed. These elevated beaches vary in perfection of preservation with their height above present tide, position in relation to drainage from the land, and the effectiveness of present wave attack. Some are as perfectly preserved as if they were merely beaches exposed at low tide. An excellent illustration of such a beach lies south of Turner glacier, where there was an elevation of 37 feet (see plate 14, figure 1); and the attack of the waves in the six years of its exposure has merely trimmed its front into a cliff, revealing an excellent beach section of cross-bedded sand.

Some beaches reveal a mere gravel veneer on a rock floor, and are hoisted so high that the waves can not reach the gravel, but are now working on the rock basement. Others are cut back by the waves and deeply gullied, and bid fair to speedy destruction. Still others are almost continuous with the present beach, being separated by only a slight notch (see plate 15, figure 1); and many are actually continuous with the present beach (see plate 15, figure 2), the boundary between the two being merely a line of drifted seaweed or a storm beach, below which grasses and shrubs do not grow. In such places the width of combined old and new beach is often remarkable (see plate 15, figure 2), being in one place fully a hundred yards.

Vegetation grows freely upon these elevated beaches (see plate 14, figure 1), but this will be discussed later. They make splendid camp sites and excellent highways for shore travel, especially at high tide. It is possible to travel on beach and bench for miles, in several parts of the

fiord, where at the former stand of the land travel along the shore at high tide must have been impossible.

ELEVATED ALLUVIAL FANS, OR DELTAS

Practically everywhere that a stream enters the fiord, in places of change of level, there is found a characteristic elevated alluvial fan. Its front is usually nipped away. Its top is dissected by the stream, forced to change from aggradation to degradation by the lowering of its base-level (see plate 16, figure 1). Many streams have intrenched themselves in their alluvial fans from sealevel to the head of the fan, and are now once more aggrading at their mouths and in the lowered channels (see plate 15, figure 1).

Accompanying this change has come a growth of both annual and woody plants upon the upper part of the fan, now no longer reached by the floods of the aggrading stream. As in the case of the elevated beaches, the nipping of the front of the fans varies with the amount of uplift and the intensity of the waves. Another factor is the amount of sediment, for some of the larger streams have built deposits in front of the fans and thus checked the nipping. Some small fans, in areas of marked uplift, have been so nipped as to form pronounced gravel cliffs from 10 to 25 feet in height, and in these cliffs, as well as in the stream cuts, the internal structure of the fans is clearly seen (see plate 16, figure 1).

TILL SHORELINES

At certain places along the present shore, but particularly in the region of marked uplift on the east and west shores of Disenchantment bay, parts of the beach now consist of compact, unoxidized blue till. The occurrence of such a clayey deposit on a beach is evidence of the recency of the movement which exposed it to the waves. How fast the clay is going off in suspension is evidenced by the muddy water along the shore wherever these till shores are wave-washed. They can not last long, for the waves will carry off the clay and round the angular pebbles and erase their glacial scratches; then normal modern pebble beaches will replace these novel ones. At present, however, uplift has brought within the reach of the sea margin the boulder clay which glaciers laid down at a former stage of extension. This boulder clay may be ordinary till or it may be an accumulation of marine silt sprinkled with scratched, angular stones floated in bergs; but its proximity to shore suggests the former explanation. These till shorelines are in all cases found either along rock shores

FIGURE 1.—ELEVATED BEACH OPPOSITE MARBLE POINT, NORTHEAST SHORE OF RUSSELL FIORD

The elevated beach is nipped in front by present waves. Mature alder thicket on right. Wave-planed elevated rock bench and sea-cliff in background, with barnacles in place on rocks 7 feet 1 inch above present high tide (see plate 17, figure 1)

FIGURE 2.—ELEVATED BEACH (7 FEET 7 INCHES) ON NORTHEAST SIDE OF RUSSELL FIORD, OPPOSITE MARBLE POINT

Man at square stands with one foot on line of highest drift seaweed, the other on boulder covered with dead barnacles. Present beach on left with no vegetation; elevated beach with young vegetation; and old land (on right) with mature alder thicket

FIGURE 1.—DISSECTED UPLIFTED ALLUVIAL FAN HALF MILE SOUTH OF TURNER GLACIER

Showing forest and topset beds. Uplift here 33 feet 11 inches. Figure of man gives scale. Iceberg-borne boulders now rest on crest of uplifted fan

FIGURE 2.—LOOKING SOUTHWARD ALONG EASTERN SHORE OF YAKUTAT BAY ACROSS YAKUTAT FORELAND AT ABOUT HIGH TIDE

Camera stood 1,600 feet above sea. Two of the new islands in Eleanor cove appear at "R"

or else in front of narrow pocket beaches; elsewhere they are doubtless deeply buried beneath beach and delta deposits.

NEW REEFS AND ISLANDS

At a number of places in Yakutat bay and its extensions the depth of the water has doubtless been very materially altered by the changes of level, but unfortunately we have no soundings to demonstrate this. In at least two places, however, new land was raised above the water away from the coastline. One of these, indicated on the map (see plate 23), lies north of Haenke island, forming a menace to navigation. There are two long, narrow islets, the larger approximately 50 feet wide by 250 feet long. Both are rounded, glaciated surfaces rising out of what is otherwise apparently a deep fiord, judging from the freedom with which large icebergs float in it. Formerly no rocks were seen here, even awash at the lowest tides, according to our Indians. Now the reefs are thoroughly uncovered at low tide and not quite concealed when the tide is high. Small icebergs strand on them and are left when the tide goes out, and stones from the melting of these bergs have already accumulated on their surfaces. From the abundance and size of the stranded rock fragments as well as from the seaweed growth on the reefs, it is inferred that these islands were shoals in the bay before 1899, and that icebergs went aground upon them even then.

Near the head of Eleanor cove, southeast of Knight island, and almost at the base of mount Tebenkof, where the mountain and foreland meet, there are four small islands which, according to our Indians, were uplifted during the earthquake (see plate 16, figure 2). Three are of rock, one of gravel, doubtless on a rock core. The two smallest are 50 feet long, the two largest each about 450 feet long and 75 feet wide in the broadest part. Their long axes are parallel and approximately parallel to the mountain front and to the fault which is inferred here (see fault line A, plate 23). They are in fact almost exactly on this inferred fault line. Before 1899 two of these islands were above water at low tide, but none rose above high tide. Now two are visible at all tides, and the other two only between mid and low tide. Thus two new reefs are now exposed, one of rock and one of gravel, and two others, previously visible only at low tide, are lifted above high tide. The highest of these reaches 3 feet above high tide, and on its crest are found dead barnacles in place, thus furnishing testimony of uplift independent of that supplied by the natives.

The Indians pointed out to us a number of places, through which

canoes can not now go, where small islands and stacks were formerly separated from the mainland by navigable water.

AMOUNT OF LAND ADDED BY UPLIFT

We have no quantitative statement to make regarding the amount of land added by this uplift. It is, however, very slight, considering the amount of uplift. The reason for this is that the shores of the fiord in the regions of marked uplift are almost everywhere steep and the water deep. Consequently the new shoreline is separated from the old by a steep grade, sometimes vertical or even overhanging, and rarely less than 30 degrees, excepting on the beaches and deltas. On the deltas and larger beaches the coast has migrated seaward sometimes more than a hundred yards; but such a width of new land is distinctly exceptional. An attempt was made at a rough calculation of the increase in size of Haenke island, where the rock slope is fairly steep, where beaches form only a small percentage of the shore, and where the uplift was marked (17 to 19 feet). This estimate is 25 or 30 feet of new land, on the average, around its entire shore.

Biological Evidences of Uplift

BARNACLES

In most parts of the fiord barnacles are abundant on the rocky shores at present sealevel; but their dead remains are also abundant on the uplifted shoreline, and very often are more abundant there than in the present tidal zone. Two species (*Balanus cariosus,* Darwin, and *Balanus porcatus,* Darwin*) cling to the rocks of the elevated shoreline (see plate 17, figures 1 and 2). Naturally in places of considerable uplift the animals have not grown to such size since the uplift as they had developed before. Among the dead barnacles great forms an inch and a half in diameter are not uncommon; but among the living forms, where the uplift was considerable, three-eighths of an inch was the maximum diameter. In many of the barnacles the inner valves are still held together by the organic tissue, though most commonly it is only the outside shell that remains intact.

These dead barnacles were found on all the uplifted rock coasts where the formation is not too fissile to retain them, and their absence was decidedly exceptional in regions where other evidence suggested uplift. They stand out clearly on the dry rock surface, especially under overhanging cliffs, and are so readily visible from a boat that their presence

* We are indebted to Dr W. H. Dall for the identification of marine animals collected on the elevated shoreline.

FIGURE 1.—BARNACLES (NEAR KNIFE AND HAMMER) IN PLACE ON SLATE ROCK 7 FEET ABOVE HIGH TIDE

North shore Russell fiord, opposite Marble point. Alders 4 years old hide other barnacles in place

FIGURE 2.—BARNACLES (NEAR KNIFE) AND MUSSELS (ON LEFT) 17 FEET ABOVE TIDE

East shore Disenchantment bay, north of Haenke island (near plate 13). Alders on right and other young plants in crevices of rocks

was often an indication of an uplifted section of shore even before the other correlated evidences were discernible. They are very commonly partly hidden by annual plants, and even by alder bushes with from one to five annual rings (see plate 17, figures 1 and 2).

Very often the barnacles were found on boulders on a beach, and it may be pointed out that while such occurrences might be critically rejected as evidence of uplift, because stones covered with barnacles could be thrown up by waves such as accompany earthquakes, in all cases where such occurrences were noted, barnacles were found adhering to adjacent rock cliffs or benches at equally high levels—positions which would preclude such objection.

These barnacles were an important feature in this study—first, because they initially called our attention to the fact of the deformation; second, on account of their function as a quantitative measure of its amount, as stated below. The fact of the presence of dead barnacles fixed to the rock in the midst of grasses and shrubs early attracted our attention. From that we went to the physiographic forms, not well developed on the site of our first observation, and from that to other physiographic evidences, to other biological evidence, and to the human testimony.

MUSSELS

Equally widespread in the fiord, though less abundant than Balanus, is the common mussel (*Mytilus edulis*, L.); and its shells constitute another of the characteristic fossils on the upraised strand. These mussel shells, which turn blue when exposed to the air, were first observed from a boat in Disenchantment bay in clusters about 18 feet above tide water, when we supposed them to be clusters of blue flowers growing in niches in the rock. Later their true nature was determined, and it was found that both there and in many other parts of the fiord the mussels were still clinging to the rocks by their hair-like byssus (see plate 17, figure 2), another evidence of the recency of the uplift. Mytilus, though often present, was not used in measuring elevations, partly because barnacles were always found where any marine life clung to the rock, and partly because the mussels were much less frequently attached than the barnacles.

BRYOZOANS

Below low tide, and in permanent tidal pools, there grows along the shores of the fiord a pink bryozoan, forming a film on the rock, which on exposure to the air turns white. On those parts of the coast which were upraised more than 10 feet, patches and bands of this bleached organism clinging to the upraised cliffs form a prominent feature, often visible

at a distance of 2 or 3 miles, giving the appearance of a whitewashed rock surface (see plate 18, figure 1). In places it still extends below the water, but in two or three sections it has been hoisted entirely out of the sea. Usually the top and bottom borders are fairly horizontally in definition; and the painted appearance of the rocks is recognized even by the natives as an evidence of uplift. This whitened surface is seen especially clearly south of Turner glacier, though it is visible in several other parts of the inlet. Abundant fossils, especially Mytilus (see plate 18, figure 1) and Balanus, occur in the whitened zone and generally extend several feet above it.

OTHER MARINE ORGANISMS

The only other marine animal found clinging to the uplifted shorelines, in such a position as to leave no question of its being in place, was the limpet (*Acniæa pelta,* Esch.). In a few instances the limpet shells were found still adhering to the rock in little protected pockets; but most of those observed on the high level shorelines were not in place and might therefore have been carried up by birds or washed up. The same is true of fragments of crabs, skeletons of fishes, and both fragments and perfect specimens of sea-urchins (*Strongylocentrotus dröbachiensis,* Mull.). Lying loose along uplifted shorelines they are not absolute evidence of change of level; but their abundance and association with other indisputable biological evidence (notably barnacles still fastened to the rock) render these other marine forms valuable as correlative evidence. A more satisfactory case was the finding of several arms of a starfish (*Heliaster* Sp.) by digging in a little rock crevice, to whose sides Mytilus was adhering in abundance, on a rock bench nineteen feet above present sealevel.

A careful search failed to discover any rockweed or other marine plants on any of the elevated shorelines, either loose or in place. That in six years these plants should have entirely disappeared by decay was to us most unexpected; but it seems nevertheless to be the case.

MINGLING OF LAND AND SEA LIFE

As previously stated, vegetation has found a footing where marine forms still cling to the rocks. Thus we find the unusual occupation of the same area by plants which can not live in salt water and animals, still in place, which can not exist without it, although all of the latter forms are dead. Besides the grasses and flowering annuals, shrubs have already sprung up, especially the willow and alder. These woody plants are notably small ones. Among numerous willows and alders which we cut down

FIGURE 1.—WHITE BRYOZOAN FILM ON 40-FOOT ELEVATED SHORELINE

West side Disenchantment bay, about 10 feet below highest dead barnacles. Many mussels in place. Alders not over 4 years old

FIGURE 2.—ALDERS AND COTTONWOOD KILLED BY SEA ENCROACHMENT

Southeast side of head of Russell fiord. Fourth of mile to the northeast the coast is elevated 7 feet 4 inches

to determine their age, it is notable that none showed more than five annual rings, and most of them had but three or four, which of itself is fairly clear proof of the association of the uplift with the earthquake of September, 1899, six years before.

One willow tree, growing on one of the most perfect of the elevated beaches (hoisted 42 feet), near Black glacier, threatened to prove an exception, for it was 10 feet high and fully 3 inches in diameter. Cutting it down, we found its heart made of dead wood, with four new rings outside. Evidently it was an uprooted tree, thrown there by the earthquake wave, and sprouted in its new location.

PARALLEL LINES OF DRIFTWOOD

On certain of the elevated beaches driftwood had accumulated previous to the uplift; and lower bands have been piled up at the new stand of the land, so that parallel lines of driftwood mark the amount of uplift. These are particularly clear near the head of Russell fiord, where driftwood is abundant. Vertical measurements between these lines, with the Locke level, form part of our quantitative determination of the deformation. In most cases these measurements correspond with dead barnacle levels on the adjacent rock shores, thus checking the determination and proving the validity of the driftwood evidence of uplift. In two or three cases, however, where no barnacles could be found in place, our measurements are based solely upon the parallel lines of driftwood.

DESTRUCTION OF LIFE

That the violent earthquake shocks destroyed much marine life is probable, and the natives assert that after the shocks the shores were lined with dead fishes. The water wave also did much destruction on the land bordering the shore, as will be shown later; but the most widespread destruction now visible is that of the life on the strip of coastline between the old and new sealevels. Here, of course, the destruction was practically absolute. Nearly everywhere the old forms are again developing in their normal habitat, newly located for them; but on all the coasts that were uplifted 10 feet or more the evidence is clear that many forms of life have been forced to begin anew in a zone which they did not previously occupy. This is proved by their small size and relative scarcity. The difficulty of starting anew is in some places increased by the smoothness of the glaciated rock surfaces at present sealevel. On numerous points, notably near Haenke island, seaweed has been able to take hold only along joint planes, and it grows therefore in short, narrow lines of small individuals.

South of Turner glacier, where the uplift was 33 to 47 feet, while dead Mytilus and Balanus are abundant all along the abandoned strand, not an individual of either, nor any of the seaweed (rockweed) so common elsewhere in the fiord were found growing at present sealevel. Here the destruction for nearly 4 miles was absolute, and in the six years since the uplift the common forms of shore life have not yet advanced upon this part of the coast. There are three apparent reasons for the failure of life to advance on this coast from other parts of the fiord: (1) the ice barrier of Turner and Hubbard glaciers to the north; (2) the sand and gravel-shore barrier to the south; and (3) the presence of an outmoving current of water, due to the glacial streams from Hubbard and Turner glaciers, and therefore coming from a region in which these marine forms are absent.*

One is impressed by such evidence with the important effect of changes of level on life, and of its possible influence on extinction of species and change of environment in regions of unstable coastlines during the geological past.

Human Evidence of Uplift

General evidence of recency

The human evidence of deformation of the shorelines has its value largely in the fact that it checks our conclusions upon two important points: First, that the elevation took place in connection with the 1899 earthquake; second, that all the movement was at once (that is, in the same month). The condition of the beaches, benches, and fans suggests that the movement was recent and that it occurred essentially at one time. The uniform perfection of preservation of certain of the marine forms points to the same conclusions. The fact that vegetation seems to have encroached on all parts of all the beaches at once (equally old plants at all levels and all parts of each beach) points to a single period of uplift; and the fact that of these plants none were found that exceeded five years in age is very definite confirmation of the conclusion that the uplift occurred in 1899.

Negative evidence of the Harriman expedition

It has already been stated that the Harriman expedition, with a corps of trained observers, including Dr G. K. Gilbert, was in the bay about three months before the earthquake. They report no evidence of recent uplift, although they landed on parts of the coast where uplifted shore-

* We are not certain that they are absent between Turner and Hubbard glaciers, for we did not visit that coast; but from a distance this coast appeared to be occupied by alluvial fans, on which neither barnacles nor mussels could thrive.

lines are very clearly preserved, as did Russell in 1890 and 1891; and both Russell and Gilbert are widely known for their studies of abandoned shorelines. Moreover, the Harriman ship, the *George W. Elder,* sailed twice very close to the site of the present uncharted reefs north of Haenke island. In the absence of other evidence, these facts might not be considered conclusive scientific proofs of the absence of uplifted shorelines in June, 1899, and they are therefore offered merely as suggestive facts bearing upon the question.

NATIVE TESTIMONY

The natives, however, tell us definitely that the uplift took place in the fall of 1899 and in connection with the earthquake at that time. They assert, moreover, that there has been no movement since then, and that there had been none in recent years before 1899.

Natives notoriously tell you whatever you want them to, especially if they can not speak your language well. Therefore in questioning the natives care was taken not to suggest by a question the answer desired. We were fortunate in having with us an exceedingly intelligent and well educated native, J. P. Henry, a Sitka Indian, long resident at Yakutat, who both spoke and wrote English well. Again and again he pointed out to us places, even before we reached them, where changes of level had occurred. He took an intelligent interest in our work and helped us materially; and in all the many cases where verification was possible we never once found him making misstatements. He, and our other native by his translation, told us of the earthquake; of the fish left stranded by the receding sea (some doubtless thrown up by the earthquake wave); of the appearance of new islands; of the uplift of beaches and sea caves; and of the whitened bryozoan film—all striking changes between the two seal hunting seasons of 1899 and 1900.

No uplift took place at Yakutat, where the whites live. These white men seldom penetrate the inner bay, and, with the exception of one or two prospectors, appear to know nothing of the details of the change of level, nor to care about it. One of the prospectors, W. H. Thompson, who knows the bay well, verified the testimony of the natives. But since the Indians hunt seal up the bay every spring, especially in Disenchantment bay, where the uplift was greatest, and are familiar with the coastline in intimate detail, their clear and definite statement as to the time of occurrence of the change requires no corroboration, once we are convinced that their testimony is honestly given, as is undoubtedly the case in this instance. As has been shown, however, even this clear and definite testimony is but one of a series of proofs, all of which point to September,

1899, as the time when, during a series of vigorous earthquake shocks, the remarkable deformation of the coastline of Yakutat bay, Disenchantment bay, and Russell fiord took place.

Evidence of Depression

Less varied in character, yet equally conclusive, is the evidence of depression, shown on a much smaller stretch of coast and naturally masked by the sea. The encroaching of beach sand on forest and the consequent killing of trees by sand-smothering, and by salt water reaching their roots, is especially well seen at the head of Russell fiord (see plate 18, figure 2).

In a number of places on the islands and shores of the foreland on the southeast shore of Yakutat bay this encroaching of the sea is also well seen. The best instance in this vicinity is on the south shore of Knight island (see plate 19, figures 1 and 2), where beach sand extends back into the spruce forest a hundred feet or more, and where waves of present storms are overturning great trees and piling their wreckage among the living spruce. Here also the rank, sedgy beach grass is found growing back in the forest, illustrating once more the battle for the shore strip between land plants and sea or shore forms. As has been stated (page 35), Ensign Miller speaks of dead trees on the shores of Miller lake; but their relation to the lake is not made clear.

None of the instances of depression can be referred to encroachment by waves, for they occur not on the exposed, but on the lee coasts. That it is actual depression of the surface is proved by the fact that over considerable areas tree roots are now bathed by salt water. It is not certain, however, that all these areas of depressed surface are actual instances of a downward movement of the crust. They all occur in unconsolidated deposits, and the depression may be due to a shaking down of these loose beds during the earthquakes. This, however, does not seem probable, since the trees are not thrown down, nor even inclined, excepting where the waves are now undermining them. That the change is a recent one is proved by the fact that many of the trees reached by the storm waves are as yet only partly dead, some of their branches still supporting the needle-like leaves.

Regions of slight or no Movement

Long stretches of coastline were not moved either up or down; but it was often difficult to be certain that there had been absolutely no movement, since a change of a foot or two one way or the other would leave only faint and uncertain evidence of the movement. In these cases simply

FIGURE 1.—SUBMERGED FOREST, SOUTH POINT OF KNIGHT ISLAND

Dead trees and beach gravel thrown back into forest among trees not completely dead. Submergence about 5 feet

FIGURE 2.—SUBMERGED FOREST, SOUTH POINT, KNIGHT ISLAND

Beach gravel in the forest and beach grass growing in forest edge

negative evidence had to be resorted to. With no dead barnacles, no discordant beach or bench, no encroachment of sand on vegetation, it was assumed that the stand of the land had been maintained. For most of the area this assumption is undoubtedly correct; because the lack of evidence of change is characteristic of certain coasts, notably on the foreland, in a part of Russell fiord, and in Nunatak fiord.

The latter case may be taken as typical of those places where negative evidence suggests no change of level, though there may have been a very slight uplift. For a mile from the glacier, along shores from which the ice has retreated since the earthquake (proved by a comparison of photographs taken in 1899 and 1905), there is no rock bench at all and little marine life. For the next mile and a half there are no dead barnacles or other marine animals, though there are many living barnacles between tides; but the higher growing seaweeds were bleached or crisped as if by a drought. This was seen nowhere else in the bay. It is probable that they would be revived by the next spring tide. For the succeeding 2 or 3 miles there is a rock bench a trifle too high for present wave work, but possibly formed by iceberg waves when the glacier front was nearer. A few dead barnacles were found, but none that we could be certain were above the level of neighboring live ones. Along this coast we were not certain whether there had been no change at all or a slight uplift; but we were convinced that the uplift, if any, did not exceed a foot.

With the facts observed and the instruments at our disposal we could not make more definite determinations in such places. Consequently we wish it to be understood that on many of the coasts where no quantitative statement of uplift or depression is given we do not mean to assert that there has been absolutely no change, but merely that we could find no conclusive proof of such change. Where the evidence suggests the probability of a slight uplift or depression, the plus (+) or minus (—) sign, with a query (?), is placed on the map (plate 23).

Effects of the Earthquake

IN GENERAL

Besides the results of the earthquake mentioned in the opening section of this paper, there are some effects still visible along the fiord which call for a word of description. They are of two classes: (1) abundant avalanches; (2) wave-swept areas.

EARTHQUAKE AVALANCHES

As in other mountain regions, avalanche effects are visible in many parts of the mountains surrounding this fiord; but they are locally far more

abundant than normal, and without any evident association with peculiarly favorable rock conditions. Moreover, they reach their best development in sections where other evidence suggests the neighborhood of a fault line to a steep mountain slope. The most abundant avalanches, far exceeding in number any seen in equal area either on the 1,000-mile trip up the Inside passage or elsewhere in the Yakutat Bay region, occur along the mountain front near Knight island, and thence northward along the mountainous shore of the east side of Yakutat bay to point Latouche. The Indians report that "the mountain face was here entirely changed in 1899;" and the vast extent of avalanches, involving hundreds of thousands of tons of rock, leads one to accept this statement as, in general, accurate.

Along the shores of Disenchantment bay, also in a region of inferred faulting, there is an excess of avalanches; but the absence of forest here makes their presence less clear and striking. We fortunately have a photograph taken here in 1890 by Russell, looking into the valley of the Black glacier 4 or 5 miles south of the Turner glacier, and at the point where, within a mile and a half, there is a change from a shoreline with no uplift to one uplifted 42 feet. A comparison of this photograph with the condition in 1905 shows remarkable changes, far in excess of what would be expected from normal weathering in 15 years. Great areas of alder and grass-covered slopes have disappeared; talus slopes are noticeably enlarged; and the mountain face is materially altered in detail.

In marked contrast is the series of hanging glaciers, not far away, south of the Turner glacier, delicately poised on the precipitous mountain side 1,000 feet or more above a shore which was uplifted 33 to 47 feet, none of which fell in 1899. One of these did slide out of its valley, however, while we were in the bay in 1905. This indicates moderate disturbance at points away from the actual fault lines.

WAVE-SWEPT AREAS

That earthquake water waves were generated by the shocks of 1899 is proved by the testimony of the natives, of the prospectors who were encamped near the Hubbard glacier, and of the white residents of Yakutat. Throughout most of the inlet no evidence of destruction by these waves is found; yet in places the evidence of a destructive water wave is very clear. Parts of the shores of the fiord are unfavorable to the preservation of records of such waves, but many sections are very favorable and yet show no evidence of an earthquake wave. For example, the low, wooded shores of Knight island show little or no signs of disturbance by the earthquake

FIGURE 1.—FOREST, 40 FEET ABOVE SEA, DESTROYED BY EARTHQUAKE WATER WAVES

East shore of Yakutat bay, mile and a half north of Logan beach. Avalanches show on mountain face

FIGURE 2.—PARALLEL FAULTS, 2 TO 10 FEET APART, GANNETT NUNATAK, HEAD OF NUNATAK FIORD

View westward out of fiord on south side of Nunatak. Faults extend north 40 degrees west (true)

wave, while north of there, half way to point Latouche, the forest is swept away over a considerable distance (plate 20, figure 1).

It is inferred from these facts that the destructive earthquake wave was local in its effects, and it is noteworthy that the two places where it has left the clearest records of its destructiveness are along the lines where we have the best evidence of faulting, namely, along the east shore of Yakutat bay, between Knight island and point Latouche, and on the west shore of Disenchantment bay, near Black glacier.

In the latter place, about at the southern end of the high-level shoreline which extends up to Turner glacier, the cottonwood forest ends abruptly approximately a quarter of a mile back from the shore, along a line which is fringed with piles of dead trunks at an elevation of 30 feet vertically above the driftwood line of the present storm beach. That this is not an elevated shoreline is proved by the fact that between it and the coast is an old dead cottonwood tree in place, eroded of its bark at the level to which the driftwood reaches, and with a little pile of driftwood on its northern side. Between this and the bay are many mature dead willows in place with dead shoots broken and bent southward.

A still clearer instance of destruction by the earthquake wave is found just north of Logan beach, about half way between Knight island and point Latouche (plate 20, figure 1). Here the present beach is littered with trees, often with branches and roots still clinging; the elevated beach is also covered with forest debris; and a still higher, older elevated beach, on which a mature forest had grown, has had its forest almost completely stripped off. Even beyond this there is a wild confusion of fallen and partly fallen trees. There is, in one locality, absolute destruction of timber up to 40 feet above sealevel; and between it and the present shore there is a tangle of fallen trees. The trees are overturned, twisted, broken, and uprooted, giving rise to such a scene of devastation as only rushing water could produce. Being evidently along a fault line, it is probable that the devastation by the tidal wave was assisted by a preliminary shaking of the gravelly soil, which rendered the uprooting of the trees here easier than in other situations.

At cape Stoss, near the head of Russell fiord, there is proof of the passage of a water wave across the low neck of land which joins the rocky cape to the mainland. This proof is the presence of enormous quantities of driftwood on the neck at levels well above that of the upraised shoreline at this point. In one place the driftwood is wrapped around an enormous boulder near the highest part of the neck and several hundred yards from the beach. The natives report that here, and in other places, their best wild strawberry beds were destroyed during the earthquake, and have not

since developed to their former condition. We found other less definite evidence of the recent presence of a destructive water wave in several parts of the fiord.

Evidences of recent Faulting

Recent faults on Gannett nunatak

At several places small faults of recent date were observed. The best and most typical instance is that on Gannett nunatak, which separates the land and sea ends of Nunatak glacier at the head of Nunatak fiord (see plate 23). This rock hill, reaching an elevation of about 1,450 feet, is made of steeply dipping gneisses and schists, striking northwestward approximately parallel to the major axis of the Saint Elias chain. The nunatak is double crested, and the southern half is crossed by scores of small faults (plate 20, figure 2), extending continuously from a few feet to over 200 yards, and with throws varying from an inch to 3 or 4 feet (plate 21, figure 1), but usually less than a foot. They extend approximately along the strike of the rock (north 40 degrees west, true north), but some small faults diverge from it, and a few short ones extend at right angles to the strike, connecting neighboring strike faults. The hade is nearly vertical, and in almost all cases the southwestern side of the fault is the upthrow side, though there are a few with an upthrow on the northeastern side. There are some fissures (plate 21, figure 2) and a few instances of small graben blocks (3 to 30 feet wide) between parallel faults (plate 21, figure 2). Some of the faults were traced up to the glacier under which they apparently passed.

Glacial scratches extend up to the edges of the faults and are there dislocated, and no striæ occur on the faces of the fault-scarps. Here and there the faults have dislocated a thin till veneer on the rock. These facts prove that the faults have developed since the ice receded from the slopes of the nunatak, not many decades ago, and possibly since Russell first saw it in 1891. That they are very young is proved by the sharp angles formed where the fault planes intersect the surface, even when the surface material is till, and by the general absence of notable talus slopes at the base of the tiny fault-scarps. It seems incredible that these fault-scarps can have been exposed to the weather longer than six years; and, although it can not be more positively demonstrated, this faulting is confidently correlated with that deformation of the crust which elsewhere in the region has been definitely determined to have occurred in 1899.

Recent faulting and avalanches

Our first observations of minor faulting and rock fracturing were made near the edge of a cliff just southwest of cape Enchantment; but the posi-

FIGURE 1.—FAULT SCARP (3 FEET) ON GANNETT NUNATAK
Cliff extends north 40 degrees west (true)

FIGURE 2.—GRABEN FAULT, 30 FEET WIDE (BETWEEN FAULT SCARPS ON LEFT AND IN FOREGROUND), ON GANNETT NUNATAK

tion was such as to make it possible to interpret the fracturing there as the result of sapping along nearly vertical strata above a stream-cut cliff. On Gannett nunatak, and in the other places, the situation of the faults precludes the possibility of this interpretation, and it is doubtful if even in the case mentioned the interpretation of sapping is the correct one.

Such shattering near a cliff edge would not only cause avalanches during the earthquake, but also prepare the way for future avalanches by opening passageways into the rock. Thus in this respect faulting is an important agent of denudation in favorable localities.

OTHER INSTANCES OF RECENT FAULTING

Similar faults were observed in a number of other places, but nowhere in such numbers as on Gannett nunatak. Recent faults were discovered on the southern slope of mount Tebenkof (strike, north 45 degrees west and north 65 degrees west, true north) and on the ridge south of point Latouche (north 85 degrees east, true north), where, at an elevation of about 1,900 feet, there are a number of faults in a moraine. Several of these have a throw of 3 feet. That the latter can not be due to landslip action is proved by the fact that they cross a valley and extend up the slope of a hill near its middle and several hundred yards away from the nearest steep slope. Recent faults were also observed by Mr Butler and the junior author on a nunatak on the west side of Lucia glacier and on the west spur at the south of Floral pass.

Thus in several widely scattered localities minor faulting was observed, and in a number of places not visited there appeared to be such faults on the mountain slopes; but no case of a single major fault-scarp was observed. The significance of these facts is considered in a later section.

Evidences of Older Changes of Level

EVIDENCE OF OLDER FAULT LINES

Largely on physiographic evidence, Russell assigned to faulting a notable part in the production of the topography of the Yakutat Bay region, and of the mountains up to and including mount Saint Elias, which he describes as a fault block recently uplifted. So far as they go, the tendency of our observations is toward the verification of Russell's generalizations, in so far as the Yakutat Bay region is concerned. The straight mountain front from Yakutat bay southeastward, with its truncated mountain spurs (plate 22, figure 1), has the form of a fault-block mountain front, though we have no facts to prove that it is not an ancient sea cliff, formed before the deposit of the gravels of the Yakutat foreland.

The straight, mountainous east shore of Yakutat bay north of Knight island, also explained as a result of faulting by Russell, certainly suggests this origin by its form.

Geological evidence in the form of abrupt difference in rock structure in a short distance (less than a quarter of a mile) seems to demand a fault line between the Coal series and the older Yakutat series along the mountain face west of Yakutat bay, and between the Yakutat series and the still older Crystalline series along the straight stretch of the lower, or northwest, arm of Russell fiord. One of these inferred lines of ancient faulting is approximately parallel to one of the recent movements.

OLDER ELEVATED SHORELINES

That faults of older date occur in this region, and that the deformation of 1899 is but one of a series of movements, associated with a progressive mountain uplift at present in progress, is suggested by the recognizable

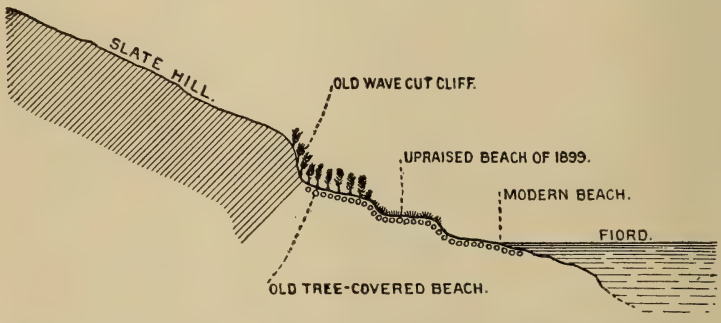


FIGURE 1.—*Cross-Section of northeast Shore of Russell Fiord, opposite Marble Point.* Illustrating the two uplifts recorded there.

remnants of older uplifted shorelines. An example of this is a wave-cut cliff with a narrow beach at the base on the northeastern shore of Russell fiord opposite Marble point (figure 1). The older beach and cliff (see plate 15, figure 1) are occupied by a dense alder thicket with bushes estimated to be over 25 years old. It rises about 4 feet above the beach which was uplifted in 1899, which is here 9 feet above present sealevel.

On the east side of Yakutat bay, just north of Logan beach, there is an elevated beach with a wave-cut cliff behind it, from which the forest has been partly stripped by the tidal wave (see plate 23 and plate 20, figure 1). One spruce tree, broken by this wave, but still in place on the beach, had 75 rings, proving this uplift to have occurred at least 75 years ago, whereas the recently uplifted strand in front of it bears only annual plants. Both the older and newer uplift on this coast vary decidedly in

FIGURE 1.—MOUNTAIN FACE RISING ABOVE YAKUTAT FORELAND

Head of Russell fiord in distance. Miller lake nearer camera. Fault line A (plate 23) passes along base of mountains. View southeast at elevation of 1,590 feet

FIGURE 2.—SUBMERGED FOREST, LOGAN BEACH, EAST SIDE OF RUSSELL FIORD

Picture taken at mid-tide

MOUNTAIN FACE, ABOVE YAKUTAT FORELAND, AND SUBMERGED FOREST

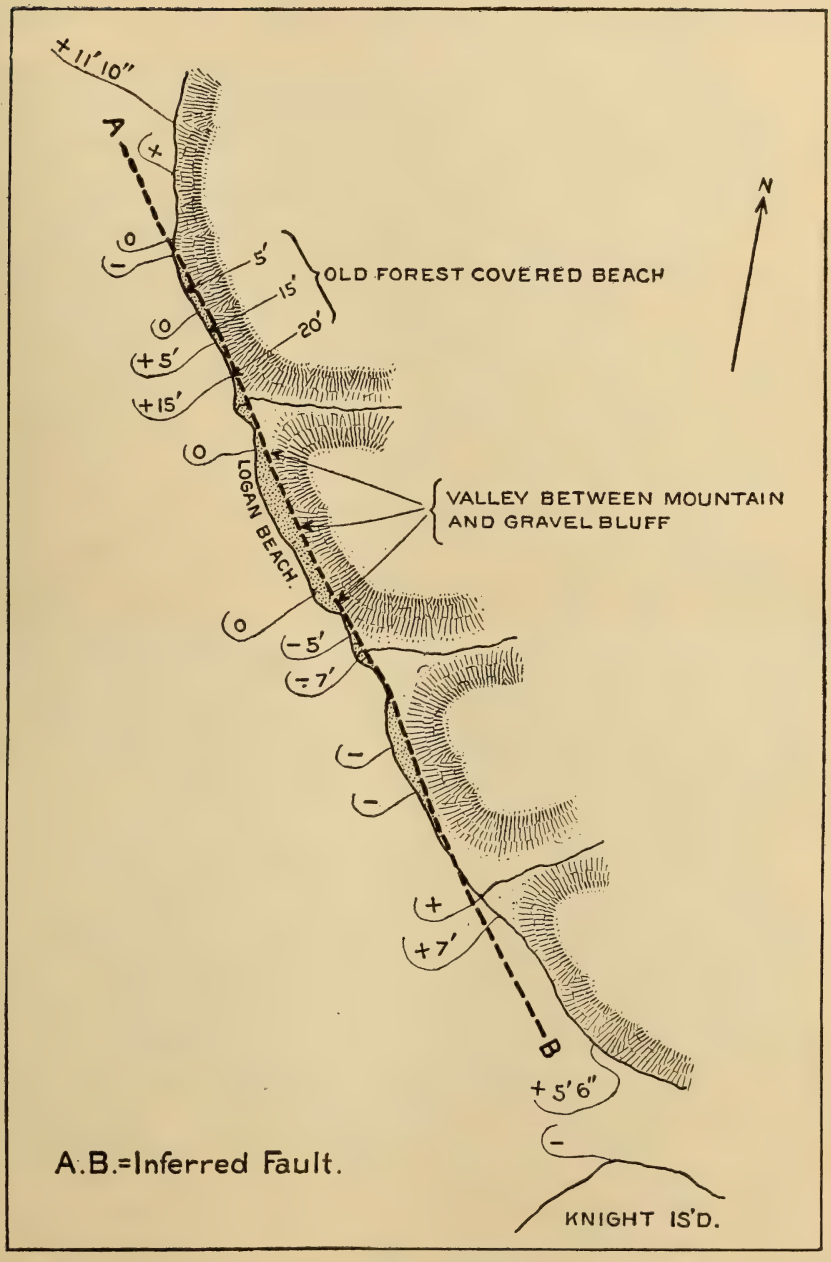


FIGURE 2.—*Sketch Map of east Coast of Yakutat Bay,*
Illustrating the conditions associated with the inferred fault, A-B, along this coast.

amount in a short distance. There are also ancient, forest-covered beaches on Krutoi and Otmeloi islands.

Near the head of Russell fiord there are elevated shorelines about 140 feet above the fiord; but these are believed to be associated with a lake dammed by an ice barrier in lower Russell fiord and Disenchantment bay during a recent advance of the glaciers.

Repeated traverses failed to reveal evidence of higher stands of the sea at levels above those described; but it is to be noted that former greater extension of the glaciers is proved for this region. We have evidence that Hubbard glacier reached down to Haenke island a century ago, and the evidence is clear that all of Nunatak fiord and more than half of Russell fiord have only recently been abandoned by the ice. At an earlier period, but at no very remote time, the entire inlet, clear to the ocean, was occupied by ice. These facts would help to explain the absence of higher shorelines if this deformation has long been in progress.

EVIDENCE OF OLDER DEPRESSIONS

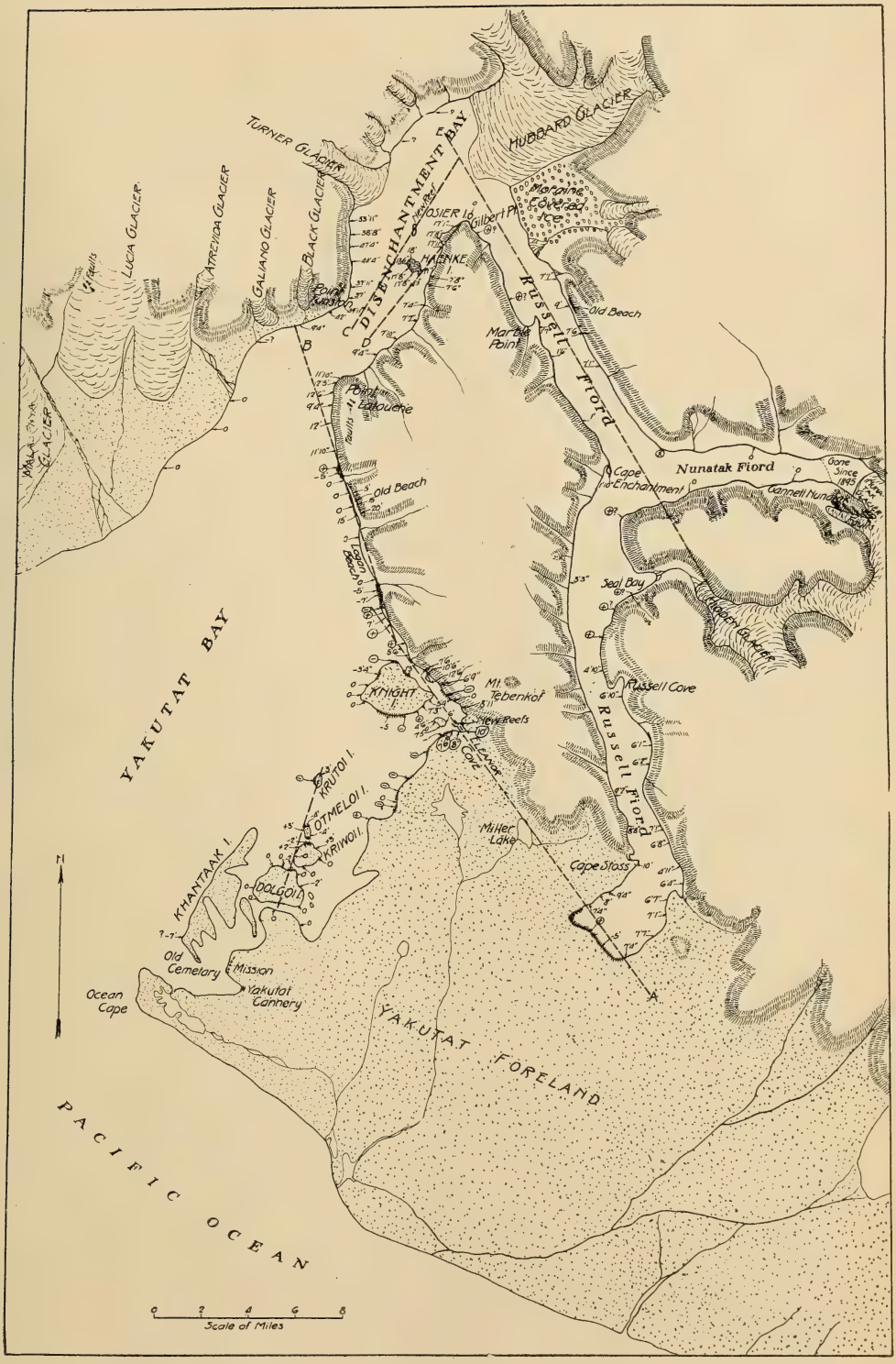
At the head of Russell fiord and at Logan beach (plate 22, figure 2), on the east shore of Yakutat bay, submerged forests appear on the beach between tides. In both cases they occur in places where evidence of uplift in 1899 is absent, and close by, and on the downthrow side of, fault lines inferred from the evidence of the deformed shorelines. In each case evidence of depression in 1899 is found not far away; but the submerged forest at the head of Russell fiord was discovered by Russell in 1891, and therefore this submergence antedates the 1899 deformation.

Statement of Quantitative Observations

METHODS EMPLOYED

Along a coastline upward of 150 miles in length we examined almost every part carefully and selected over one hundred points as suitable places for quantitative measurements. Our method of measuring the change of level necessarily varied with conditions; but wherever possible our measurement is the vertical distance between the highest living and the highest *fixed* dead barnacles, in a place where the latter are well preserved. For obtaining these measurements we used the Locke level and a graduated rod, the greatest elevations being checked by aneroid.

This method, like any other we could devise, was subject to a small error; but, owing to the widespread abundance and excellent preservation of the barnacles on the elevated shoreline, the amount of this error could not be great. Care was taken to select the most favorable sites, and very



SKETCH MAP OF YAKUTAT BAY

Quantitative measurements of deformation of shorelines indicated in feet (') and inches (")

often two or more observations were made close together as a check on the one recorded. The possible error is all on the side of conservatism for two reasons. In the first place, along the elevated shoreline occasional barnacles are still living just above the zone of barnacle growth, having been able to survive these six years with an occasional bath of salt water from waves at high tide. Consequently when we took the highest living barnacle, always searched out very carefully, it was often the only living one among many dead forms and several inches above the upper limit of abundant live barnacles. In the second place, the highest dead barnacle actually attached to the rock (and we took account of no others) was often probably not as high as barnacles had grown at the former level of the sea. If the conservative error on both ends could be corrected, we have no doubt that it would often increase the uplift by 6 inches or a foot, but would never diminish the amount stated.

In a very few places where living barnacles were absent from the present shoreline, as along the coast south of Turner glacier, our measurements are between the high-tide mark and the top of the zone of abundant dead barnacles, which was assumed to represent high tide on the old strand. On the elevated beaches we made one or two measurements between parallel lines of driftwood; and two or three measurements were made between the lower limit of land plants on the ancient beaches and the lowest old bushes above it, a possible error of only a foot or two. It should be pointed out that the greater number of our measurements (approximately 80 per cent of them) were made by the conservative method of measurement between highest living and highest dead barnacles, and that all other cases, where another method was necessary, checked well with closely adjacent localities where barnacle observations were possible. The coast south of Turner glacier is an exception, for here barnacles were used only at the upper limit.

Our measurements of depression are much less exact. For these we measured the vertical distance between the base of the lowest tree in place and of the highest on which beach gravels were being piled at the time.

CHANGES OF LEVEL ON THE FORELAND

Taken as a whole, the foreland and its associated islands may be considered as a region of no change of level, though with small areas of slight depression, usually too slight for quantitative measurement. On the west side of Yakutat bay, from opposite point Latouche to the Kwik delta, the shoreline was studied carefully, but no change in level could be detected on the foreland. On the southeast side of the bay, near the mountains, both on Knight island and on the mainland, the changes of

level are very irregular, but on the whole show uplift. A short distance out from the mountain base the uplift ceases, and the same is true at the head of Russell fiord. In all cases, that is on four coasts (both sides of Yakutat bay and Russell fiord) (plate 23), there is a change from an upraised to a depressed or stationary coast in a short distance—within a hundred yards southeast of Knight island and on the southeast shore of the head of Russell fiord and within a mile on the other two shores.

The longest stretch of the foreland coast studied lies between Knight island and Yakutat. Here, both on the shores of the foreland and in the maze of channels between the islands, the usual condition is that of forest coming down to the very water's edge, and therefore giving a very delicate register of change of level. Along most of the coast there has evidently been no change whatsoever; but in two or three places there has been a very slight uplift, and in a number of places the coast has been depressed, especially among the small islands. There is also evidence of older change of level in two or three places, but notably on the northeast end of Krutoi island, where there is a recent uplift of 3 feet, and back of it a beach and wave-cut bluff of much older date with a mature forest growing on it. This older uplift was between 5 and 10 feet.

At and near Yakutat and in the slough near Ocean cape, there is no evidence of change of level. Whether the destroyed cemetery on Khantaak island is evidence of depression or merely the work of the earthquake wave was not determined; but just west of this, on the ocean shore of the island, there is a condition of forest encroached on by present waves which suggests depression of about seven feet. It may, however, represent sea encroachment on the shore, and is therefore considered only tentatively as possible evidence of local depression.

CHANGES OF LEVEL ALONG THE MOUNTAINOUS EAST COAST OF YAKUTAT BAY

The changes of level along this coast are very irregular. Near Knight island the uplift varies from 5 to 12 feet 6 inches, and there are marked variations in short distances. Along the coast north of Knight island to within 4 or 5 miles of point Latouche the average condition is either that of no change of level or else of depression (see plate 23 and figure 2); but where the coast turns eastward, both near Knight island and near point Latouche, uplifted shores begin abruptly, reaching a maximum of 10 feet near Knight island on the mainland, and of 12 feet 6 inches near point Latouche.

Along the straight stretch of coast between the uplifted parts there is a general condition of gravel foreland forming a narrow strip between the mountains and the sea (figure 2). In one part, however, just north of Logan beach, the mountains come down close to the sea, and here for a short distance there is a recently elevated shoreline 15 feet above present sealevel, but descending abruptly northward, and disappearing in less than a half mile. Back of it is the older, spruce-covered beach already described, which descends northward more than 2 miles before being lost. As shown in a later section, these phenomena are believed to be related to a fault line close by the mountain base.

CHANGES OF LEVEL IN DISENCHANTMENT BAY

At point Latouche the uplifted shores are 11 to 12 feet above present sealevel, but perceptibly decline northward, for most of the distance between point Latouche and Haenke island (on the east side) being between 7 and 8 feet. At Haenke island, however, the raised shorelines are 18 or 19 feet, and this marked uplift abruptly appears on the peninsula northeast of Haenke island (see plate 13 and plate 17, figure 2), and extends nearly to Gilbert point, where it disappears equally abruptly. Within a mile, at Gilbert point, there is a change from no uplift on and near Osier island to 17 feet 1 inch just southwest of it. It is in this region of marked uplift that the new reefs appear just north of Haenke island.

On the west shore of Disenchantment bay the first rock cliff south of Turner glacier (a quarter of a mile from the glacier) shows an uplift of 33 feet 11 inches; and this remarkable shoreline, the most perfect as well as the highest in the region (see plate 14, figure 2; plate 16, figure 1, and plate 18, figure 1), attains an elevation of 47 feet 4 inches within a distance of a mile and a half. Just below point Funston the elevation is 42 feet, and south of that it rapidly descends. No accurate quantitative measurements were possible in this region of disappearance, but the uplift evidently extends to the Black glacier alluvial fan, where on the north side it is estimated to be about 30 feet, and on the south side, a little over a quarter of a mile away, 9 feet. South of this no evidence of uplift was found; but on the alluvial fan of Galiano glacier, a mile and a half southwest, there is indication of slight subsidence, and beyond that no reason for inferring any change of level.

From these facts it is evident that the shores of Disenchantment bay have been greatly uplifted (the highest in the fiord), and that they have been differentially deformed. While the changes in amount of uplift occur within short distances here, as in other parts of the fiord, they are

not traceable to a single sharp break, but are apparently the result of decided change taking place in a narrow zone.

It would be interesting to know what effect a 34-foot uplift had on the crevassed front of Turner glacier, for there is evidence of this great elevation up to the very edge of the ice. Gilbert suggests that the front of this glacier is floating, and if this is true the effects of uplift would have been more destructive than if the ice rested on the bed of the fiord. We were unable to determine what effect the uplift had; but it is noteworthy that the form of the ice-front has been materially changed since Gilbert photographed it in 1899.

CHANGES OF LEVEL IN THE NORTHWEST ARM OF RUSSELL FIORD

The northeastern shore of this fiord, from the Hubbard glacier to Nunatak fiord, shows uniformly an uplift of considerable amount (plate 15, figures 1 and 2); but the conditions for accurate measurement of the uplift were not usually present on the friable slate rock and extensive beaches which constitute this shore. Four good observations were secured, one of them on the beach (7 feet 7 inches), the other three on barnacles on the rock (plate 17, figure 1), giving measurements of 7 feet 1 inch, 7 feet 6 inches, and 9 feet. It is along this coast that an older beach, covered with mature alders, was discovered (see figure 1).

On the southwest shore, on the other hand, although the rocks are very favorable for preservation of barnacles, we nowhere found evidence, either of a physiographic or a biologic nature, of uplift of over 2 feet. On most of the coast the evidence is wholly negative, but at four points we found dead barnacles on a slightly elevated bench from 1 foot to 1 foot 10 inches above the highest living barnacles. The evidence is convincing that there is a marked difference in the uplift on the two sides of this narrow, straight stretch of fiord.

NUNATAK FIORD

We have already described the conditions on the southern shore of Nunatak fiord, where there is no clear proof of change of level, but a possibility of an uplift of a foot or less. The northern shore of the fiord likewise gave no proof of change of level; but this coast is wholly beach and alluvial fan on which a moderate uplift might easily be indistinguishable. The difficulty of discovering an elevated shoreline in this part of the fiord is increased by the fact that the recession of the glacier has been so recent that abundant vegetation has not advanced far up the fiord, and this aid to detection of uplifted beaches is therefore absent. However, the fact that no evidence of change of level could be discovered in this fiord, while

not proving entire absence of change, is believed to demonstrate very slight, if any, change.

CHANGES OF LEVEL IN THE SOUTH ARM OF RUSSELL FIORD

At cape Enchantment there is evidently an uplift of less than 2 feet, and several miles south of this, opposite Seal bay, of 3 feet 3 inches. Between these two points there is a succession of slightly elevated beaches and fans; but on the east side of the fiord, while a slight uplift is indicated, we could got no definite measurement until a point was reached 2 or 3 miles south of Seal bay. Conditions along this eastern coast are perfect for the preservation of evidence of uplift, and our failure to find definite evidence convinces us that the uplift here was at best very slight. Quite abruptly, however, just north of Russell cove, a wave-cut bench rises, and on it we found dead barnacles 4 feet 10 inches above the highest living ones. South of this the bench slowly rises, reaching an elevation of 9 or 10 feet on the west side and 7 or 8 feet on the east side of the fiord (plate 14, figure 1). At the very head of the inlet, in the fist-shaped area in the foreland, there is a change in a very short distance on both sides of the bay from an uplift of 7 feet 4 inches to a depression (plate 18, figure 2).

Interpretation of Observations

IN GENERAL

Our observations lead us to the conclusion that here, in a non-volcanic region, the land is still rising. Moreover, there is definite evidence that earlier movements have preceded that of 1899. How widespread the effects of this last movement were on the Pacific coast is not yet known; but the destruction known to have occurred in September, 1899, at the front of the Muir glacier, 140 miles away, suggests the possibility of its extension this far, and observations in that region will be awaited with interest. At Dundas bay, near the entrance to Glacier bay, we landed for a few hours, but found no evidence of change of level; and there was none at Sitka. On our way down the Inside passage we looked for evidence of change of level, but without success, excepting in the narrow passage just north of Ketchikan, several hundred miles farther southeast, where there has been a recent uplift of unknown date and amount, the evidence of which is visible from the steamer.

In the region of our detailed studies it is evident that the uplift was differential and that the movements were complex, resulting in a distinct deformation of the coastline and bordering land. The exact nature of

these differential movements is not certain in all cases, though some conclusions regarding them seem clear and well founded.

MOUNTAIN-FRONT FAULT

That there is a zone of narrow width, just outside the mountain base, where uplift is replaced by either depression or no change, is clearly shown at four points. This suggests the presence of a fault line near the mountain base. If such a line is projected (see fault line A, plate 23) it passes through three of the areas where uplift is replaced by depression or no change, but would need to be bent slightly to reach the fourth at the head of Yakutat bay on the west side. From this evidence a fault line is inferred along the face of the mountain from the head of Russell fiord to Knight island.

Additional reason for suspecting an older fault here is found in the topography already described—a straight mountain front with truncated spurs reaching out to nearly the same line (plate 22, figure 1). Along this line, northeast of Knight island, there is also an unusual development of avalanches. Moreover, the amount of uplift along it varies greatly, as it naturally would along a fault with the downthrow side dragged upward, and with the fault line not a single break but a complex of parallel fractures, as seems to have been the case in this region, where the change across the fault line is not an abrupt scarp, but occupies a zone of some width. The statement of Ensign Miller that trees are destroyed on the east and west side of Miller lake is interesting, since this is exactly where we place our fault line on entirely independent evidence.

Harmonious with the interpretation placed on the facts in this region is the appearance of the four small islands east of Knight island, exactly where the inferred fault is believed to pass, and with their long axes parallel to the fault line. We do not place this fault line outside the zone of uplift because it is believed that some of the upraised coast near and on Knight island is due to updrag on the downthrow side.

POSSIBLE MINOR FAULT SOUTHWEST OF KNIGHT ISLAND

There is the possibility of a second fault of minor character along the islands between Knight island and Yakutat (see fault line, plate 23). The evidence of this is not convincing, and this fault is proposed solely on the basis of the fact that there is a rather remarkable linear arrangement of uplifted and depressed areas in the midst of a region which, in general, shows no sign of change in level. The fact that earlier changes of level are recorded in these same places by older uplifted beaches, and that similar shorelines were not discovered elsewhere in the foreland, is

a part of the evidence on which a fault line is inferred with some doubt along the axes of these islands.

FAULT ALONG EAST SHORE OF YAKUTAT BAY

Much clearer evidence of a fault line exists along the mountainous eastern shore of Yakutat bay (see unlettered fault line B, plate 23). Here the mountain front is straight, steep, and has spurs truncated along a straight line. The mountain face is scarred by numerous avalanches, and the shores at its base were washed by the most destructive tidal wave recorded in the region (plate 20, figure 1). For much more than half its length this shore shows no elevated strands; but they begin where the coast bends away from the straight line on both the north and south end; and near the middle, where the mountain slopes come down close to the sea, there is an upraised ancient beach and, parallel to it, an uplift belonging to the 1899 series (see figure 2).

We are able to suggest no other explanation for the phenomena recorded here than that of a fault close to the mountain base, lifting the hard rock of the mountains, but not raising the gravel forelands which skirt most of this straight coast. In this connection it is notable that behind the broadest part of the narrow foreland, at Logan beach, there is a valley between the foreland and the mountains, whose formation by earlier faulting is easy to understand, but difficult of explanation in any other way. That the earthquake shock was violent here is proved by the fact that a gold miner's log cabin on the gravel bluff above Logan beach was partially demolished, unroofed, and thrown part way off of its foundations during the earthquake of 1899.

We are not absolutely certain whether to correlate this fault with the one inferred farther southeast along the mountain front (plate 23, fault A), which it intersects at a low angle, assuming the two to be connected by a slight bend, or whether to consider it a separate and distinct fault. The later interpretation is placed on the map, but we have no evidence to prove this interpretation as opposed to that of a single continuous, slightly curved fault line. It is a notable fact that this fault line, extended, strikes the western side of the head of Yakutat bay exactly at the point where the great uplift south of Turner glacier dies out.

FAULTING ALONG DISENCHANTMENT BAY

The great uplift (reaching over 47 feet) on the west shore of Disenchantment bay; the lesser, but still great (18 to 19 feet), uplift on Haenke island and the shore of the peninsula north of it; and the moderate uplift (7 to 9 feet) along most of the east shore of Disenchantment

bay seem to demand at least two lines of faulting. One of these (see line C, plate 23) is inferred between Haenke island and the west shore, one (line D, plate 23) between Haenke island and the east shore. No other evidence of these inferred faults was discovered than the remarkable differences in uplift in short distances. The rapid descent of the elevated shoreline from 17 feet to no change at Gilbert point is believed to be related to the fault line along the northwest arm of Russell fiord.

FAULT LINE IN NORTHWEST ARM OF RUSSELL FIORD

It has already been shown that geological structure indicates the existence of an older line of faulting along this straight reach; that an uplifted beach of older date exists on the northeast shore, but none was discovered on the southwest shore; and that the uplift of 1899 upraised the northeast shore from 7 to 9 feet and the southwest shore nowhere more than 1 foot 10 inches, so far as we could see. These facts point clearly to a fault line along the axis of this part of the fiord (see fault line E, plate 23).

Nunatak fiord gives us no proof of change of level, though the nunatak at its head is badly fractured.

SOUTH ARM OF RUSSELL FIORD

From a region of very slight uplift near cape Enchantment, and a possible slight uplift on the opposite shore, there is a rise in the elevated shore line to a maximum of 10 feet near the head of the inlet, where in a short distance the uplift is abruptly replaced by depression on the foreland along the line of the inferred mountain-front fault (line A, plate 23). There is no evidence of faulting along the axis of this part of the fiord; and no proof of an earlier uplift was discovered.

MINOR FAULTING

In addition to the major lines of faulting which we have inferred, evidence exists at several widely scattered points proving a minor shattering of the crust, as stated in the preceding paragraphs. These places have in no case been found along the lines of inferred major faults, but in all cases where observed they appear to be due to a minor shattering in the larger uplifted blocks. The fact that no uplifted shorelines occur near the shattered Gannett nunatak is not significant, since the present coast of the nunatak was more nearly inclosed by ice in 1899, and a few years previous to that (in 1891) was completely inclosed; so that by 1899 there had not been opportunity for the development of a shoreline on the nunatak.

FOLDING VERSUS FAULTING

Both in the field and since our return we have attempted to place the interpretation of folding on the phenomena of deformation described, but

without success. Opposed to folding are four significant facts which seem to eliminate it as an hypothesis. In the first place, the lines of deformation extend in too many directions. In the second place, the zones of gradation between areas of different degrees of deformation are exceedingly narrow, while the intervening areas of uplift are very broad. In the third place, the minor faulting proves dislocation in parts of the region. Finally, faulting is proved by the series of earthquakes and their destructive avalanches and water waves.

NATURE OF THE DEFORMATION

Briefly summarizing the inferences which the facts seem to warrant, we conclude that in 1899 there was a renewal of mountain growth, uplifting that part of the mountain front bordering the Yakutat bay inlet to different amounts—7 to 10 feet on the southeast side of the bay and 40 to 47 feet on the northwest side. This uplift occurred all within a little over two weeks and mainly on a single day (September 10). It was complicated by movements along secondary fault lines, which produced at least three (and perhaps more) distinct major blocks, as follows: (1) The area between fault lines A, B, C, and E (plate 23), including all the peninsula and a part of the mountains east of the south arm of Russell fiord to an unknown distance toward the southeast; (2) a block west of fault line E (plate 23), extending westward an unknown distance from the west shore of Disenchantment bay; (3) a block extending northeastward for an unknown distance from the northeast shore of the northwest arm of Russell fiord. The first and largest of these blocks, that including the peninsula, is apparently tilted upward toward the southwest.

Accompanying this faulting was a minor fracturing apparently due to local adjustments in the tilted blocks. Doubtless this minor fracturing is much more common than our observations indicate, for it was discovered in more than half of our expeditions into the interior when we went out of the valleys away from the seacoast.

TOPOGRAPHIC SIGNIFICANCE

That this faulting may be part of an important process by which the main lineaments of topography in this region were developed is evident. The straight mountain front, the straight mountainous eastern shore of Yakutat bay, and the straight northwest arm of Russell fiord all bear evidence of faulting during this recent period of uplift, and the evidence seems to demand the presence of two fault lines along Disenchantment bay. How far this process of faulting can be applied in explanation of the initial outlining of the fiords is not certain from any facts we could

gather; but of one thing we are certain: In spite of the parallelism of the fault lines to several reaches of the fiord, and in spite of their possible importance in determining the main lineaments of the valleys, the present depth and form of the fiords are assignable not to faulting but to glacial erosion. The evidence of this is clear and convincing, but the statement of it can not be made in this paper.*

Comparison with Other historic Uplifts

While there are many evidences of changes in level during recent geological time, in widely separated localities, some of a slow secular nature still in progress and involving extensive areas, some evidently abrupt and involving smaller areas, the great majority of these give us no clue either to the time or nature of occurrence or to the amount of uplift at a given period.

Some instances are fairly definite in these respects, and some locate the period of uplift and determine its amount with exactness. A preliminary examination of the literature fails to find a single instance in which an uplift approximating in amount that of the Yakutat Bay region, in its maximum, is described as having occurred at a single period of disturbance. Compared with the historic changes of level associated with definite earthquakes, the Yakutat Bay deformation therefore stands conspicuous. It is apparently the greatest historical change of level (47 feet 4 inches at the maximum); it combines the various classes of evidence—beaches, benches, sea caves, marine animals, human testimony, as in South America (1822, 1835, 1839); new reefs, accompanying faulting, as in New Zealand (1855); combination of elevation and depression, as in India (1811); and it adds the new types of evidence of dissected alluvial fans and uplifted till shorelines, besides furnishing the most complete interrelated evidence of all sorts in practical agreement.

* See Tarr and Martin: Bull. Amer. Geog. Soc., vol. xxxviii, 1906, pp. 145-167.